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# DEVELOPMENTS IN THE APPLICATION OF GEOPHYSICS TO GROUND-WATER PROBLEMS

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# DEVELOPMENTS IN THE APPLICATION OF GEOPHYSICS TO GROUND-WATER PROBLEMS<sup>†</sup>

By CARL A. BAYS

By STEWART H. FOLK

**A**PLIED GEOPHYSICS—THE practical use of geophysical principles—has grown phenomenally within the past several decades. Thirty years ago geophysical investigations were limited to the realm of “pure” science and to exploration for metalliferous deposits. Today various geophysical methods are used in exploration for ground-water, petroleum, coal, sand and gravel, and many other non-metallic minerals as well as the metallic ores, and in investigating the geological and engineering problems that arise from drilling for and producing water, oil and gas, and in constructing dams, highways, airports, and buildings.

These and other fields of investigation have contributed to present methods and techniques of geophysics, but because of the large financial returns in the petroleum industry, it has been there that applied geophysics has made its greatest advance in recent years, particularly in subsurface or well surveying. Ground-water work, like other provinces of engineering, can profit from adaptation of new developments in all scientific and industrial fields, but it can benefit most from the advancements made in the petroleum industry where the problems are so similar and the progress so great.

## Geophysical Methods Used in Ground-water Work

A large share of all geophysical exploration, and of course all ground-water exploration, is for the purpose of determining the conditions beneath the earth's surface. Toward that end there are two approaches: (1) surface surveys, made on top of the ground; and (2) subsurface surveys, made in wells or boreholes and mines.

Almost all the methods and techniques of geophysics have been tried and many of them have been found successful in ground-water work, but the electrical methods receive the widest application in both surface and subsurface surveying at the present time.

## Surface Surveys

Most surface surveys in ground-water work are made in order to locate ground-water supplies. Electric resistivity, electric potential, magnetic, seismic, gravitational, thermal, radio, and radioactive methods have been used for that purpose with varying degrees of success by a number of organizations and individuals in many different areas<sup>1,\*</sup>.

Measurements of the earth's electric resistivity (earth-resistivity surveys) have been found very useful in locating water-bearing sands and gravels, and for the past decade the Illinois Geological Survey has employed such surveys extensively in ground-water exploration in Illinois. This work has been done by a number of members of the Geological Survey staff although not by the writers.

Of the one hundred surveys made since 1936, 50 located sand and gravel water supplies which have been developed. In eight areas which were tested by drilling in spite of unfavorable surveys, the drilling confirmed the surveys and the areas were abandoned. Seventeen areas were abandoned because of unfavorable reports by the surveys. There have been no reports of testing on the other 25 surveys.

A modified Gish-Rooney circuit is used by the Illinois Geological Survey in its earth-resistivity surveys (Fig. 1). Two steel electrodes are driven into the ground some distance apart and two copper electrodes are set between them. An electric current (commutated D.C.) is passed through the ground between the steel electrodes, and the potential drop across the space between the copper electrodes is measured. The apparent resistivity of the earth to a depth approximately equal to the distance between the copper electrodes can then be calculated. The depth of investigation is varied by changing the spacing of the electrodes. Measurements of resistivity to great depths can be made by this method,

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\*References are given at end of report.

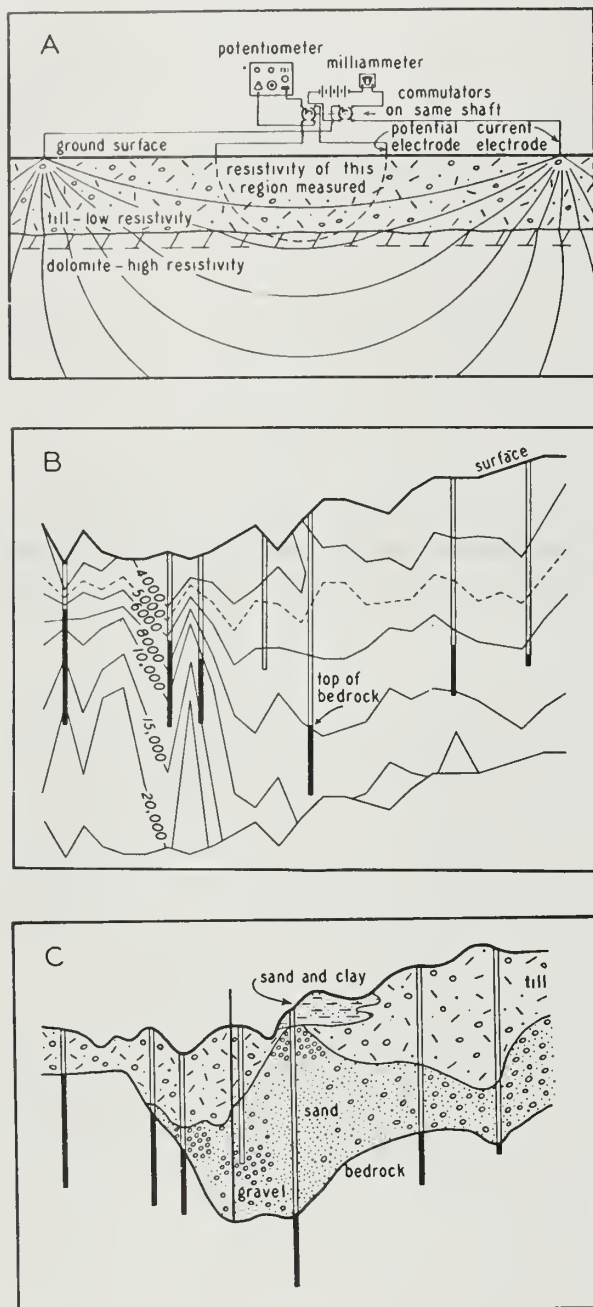


FIGURE 1.

Earth resistivity surveys. A: diagram of circuit and current distribution, B: graphic profile of earth resistivity along a traverse; bed-rock penetrated in wells shown in black, C: geological cross-section along traverse in B based on interpretation of resistivity data and well records.

but because most of the water-bearing glacial and fluvial sands and gravels in Illinois occur within 300 feet of the surface, deeper measurements are seldom made by the Geological Survey.

Earth-resistivity surveys have been most successfully applied in Illinois in areas where the water bearing sands and gravels, which have relatively high resistivity values, overlie materials of low resistivity, such as shale and glacial till. From recent work,

however, it appears that if sufficient geological information from drill-cuttings and well logs is available, resistivity surveys may be used successfully in areas where the water bearing sands and gravels lie on limestone or dolomite bedrock of high resistivity. Of course some knowledge of the subsurface geology is essential for the proper interpretation of the electrical data in any area.

If a survey indicates the presence of water bearing deposits, locations are recommended for test-drilling so that samples of the sand or gravel and water may be obtained before the producing well or wells are drilled. Large savings are effected by the use of earth-resistivity surveys which reduces the number of test-holes needed for exploration by random drilling.

### Subsurface Surveys

Electric resistivity, electric potential, thermal and sonic methods have been used in surveying or "logging" water wells. Helpful auxiliaries, although not strictly geophysical instruments, are devices for measuring the diameter of the hole from top to bottom of the well, for measuring the rate of flow of fluids throughout the well bore, for testing each formation separately as drilling progresses, for sampling the water at different places in the well, and for taking pictures of the walls of the hole both above and below the surface of the water. Some of these were developed originally for use in water wells but most have been borrowed from the oil fields.

There are a number of other geophysical methods and auxiliary instruments now used in oil and gas wells that would be of value in water wells. These include seismic, magnetic, radioactivity, neutron-bombardment, fluid opacity, and hydrogen ion concentration surveys, devices for shooting bullets that perforate steel casing and shatter sandstone formations, and devices that take samples of rock from the wall of the hole after a well has been drilled. Other methods and instruments which give promise for use in both water and oil wells are in the experimental stage, and there are in view still others that have not yet reached the drawing board. The use of any or all of the above methods and tools in surveying wells is known as "geophysical logging."

### Geophysical Logging of Water Wells

Since 1942 geophysical logging methods have been used by the Illinois Geological Survey to investigate geological conditions and various problems of the deep cable-tool water wells of northern Illinois.

Geophysical logs have been made of 21 wells, using a number of different methods and instruments in each well in order to study the many problems encountered. Most of the instruments first used in this work were those employed in logging rotary-drilled oil wells in southern Illinois, but as the work progressed additional methods and tools were introduced or developed so that the usual practices of oil-well logging were modified to suit the conditions in water wells. Surveys of deep water wells in Illinois now include most or all of the following logs: electric log, comprising the electric potentials and resistivities of the formations and their fluid contents; electric resistivity and the temperature of the fluid in the well bore; rate and direction of fluid movement in the well bore; hole diameter; additional potential and fluid resistivity logs run after dissolving salt in the water; and additional potential and temperature logs run while the hydrostatic head on the formations has been increased by flowing water into the well. The data available from geological investigations, particularly the study of well-cuttings, and the results of the geophysical surveys are integrated in order to solve the problems presented by most wells.

### Geophysical Logging Equipment

The geophysical logging of Illinois water wells has been done with modern equipment that is operated by oil-well service companies in southern Illinois and other oil producing areas. Both of the companies that operate in Illinois, the Halliburton Oil Well Cementing Company and the Schlumberger Well Surveying Corporation, have participated in the work to date, and the fine cooperation of these companies and their employees has greatly facilitated the studies.

The logging equipment has been operated by the personnel of the service companies, but most of the

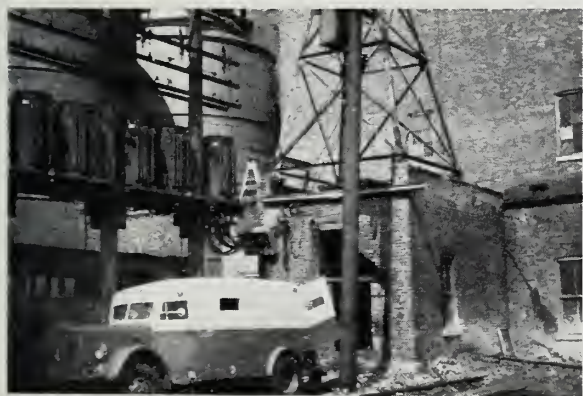


FIGURE 2.

Geophysical logging truck in operation on an industrial well in northern Illinois.

work of assembling, drafting, and interpreting the logs has been done by members of the staff of the Illinois Geological Survey.

All of the equipment and instruments of a logging unit operated in Illinois are mounted on a single truck (Fig. 2). The logging units of the different companies incorporate the same basic features but of course differ in many particulars. The essential elements of a logging unit (Fig. 3) are: a cable



FIGURE 3.

Rear of logging truck showing winch and spool for cable, the cable, lines for grounds, speaker, and measuring device.

(which bears one or more insulated conductors) for running the tools into the well; a winch for spooling the cable; a measuring device for accurately indicating the logging depth; the instrument panel, on which are mounted the galvanometers and other apparatus that are necessary to make the various geophysical measurements; a recording device, usually a camera, by which the logs are recorded on photographic film or paper; and the tools themselves. Some of the most commonly used tools are shown in Figure 4. They are the electric logging electrode (A), hole caliper (B), well surveying thermometer (C), current meter (D), and the "salter," a device used for dissolving salt in the water throughout the well (E). The current meter and salter are not supplied by the logging companies; those shown in the picture were made by the Geological Survey. The

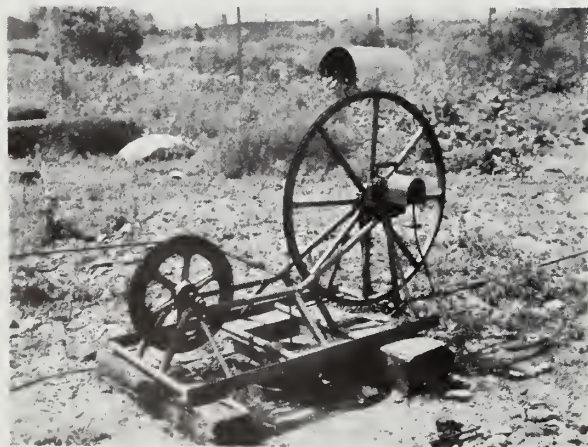


**FIGURE 4.**

Some of the tools and devices used in making geophysical logs: A: Electric logging electrode for potential and impedance surveys, B: Hole caliper, C: Well-surveying temperature electrode, D: Current meter, E: Salter, F: Two-way speaker which is connected with the recorder cab in the logging truck.

logging trucks carry their own power sources, both generator and batteries, have dark room facilities for developing the film that bears the logs, and have two-way speakers (F) for communicating between the recording cab and the well curb.

Because of the importance of accurate measurements in wells, the measuring devices merit special attention. Two types are in common use, one connected mechanically with the recording camera and driving it so that correct depths are recorded on each log, and the other (Fig. 5), employing a selsyn



**FIGURE 5.**

Measuring sheave and logging cable in operation. The counter and selsyn transmitter are geared to the large sheave and connected by cable with the camera in the logging truck.

transmitter system operating the camera by an electric motor.

### Electric Logs

The electric log consists of curves or logs that represent the apparent values of the electric potential

and electric resistivity or impedance of the wallrocks and their contained fluids throughout the uncased portions of a well. Measurements of potential and resistivity are made with a traveling electrode assembly (Fig. 6) that incorporates one or two current



**FIGURE 6.**

Logging electrode assembly used for making potential and impedance logs.

electrodes and several pick-up or potential electrodes spaced at different intervals, and with a circuit so designed that both potential and resistivity values can be measured and recorded simultaneously. Both curves are recorded and printed on the same strip, the potential in a column at the left and the resistivity in a column at the right (Fig. 7).

The electric potentials of earth and rock materials result from a number of causes, chief of which seem to be electrofiltration and electrochemical phenomena<sup>2</sup> such as solution-concentration differences and selective polar adsorption by certain minerals in the formations<sup>3</sup>. Fortunately the potentials produced by the different phenomena apparently are cumulative for most formations and consequently accentuate the relief on the potential curve. The electrofiltration potential is related to the permeability of the formation and to the difference between the hydrostatic head of the formation and the head in the well bore. Flow from the well into the formation produces a

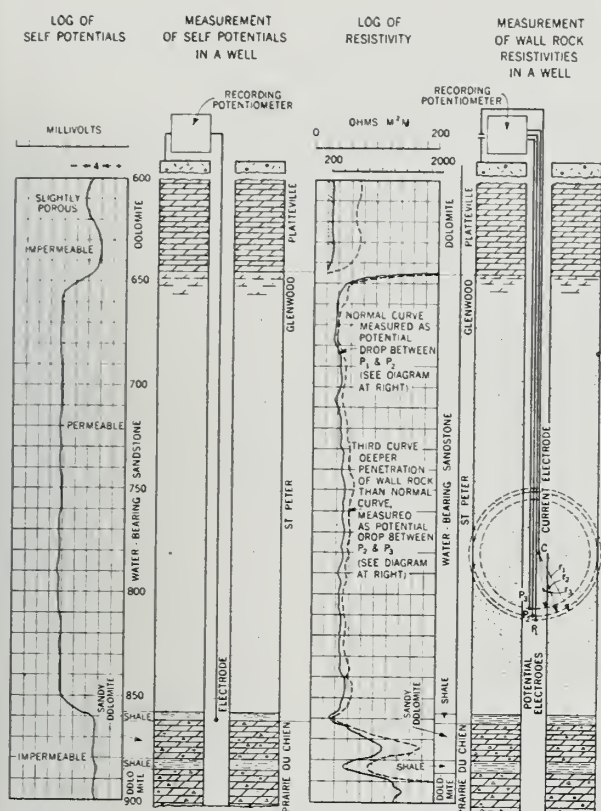


FIGURE 7.  
Electric log.

logging operations that involve direct current circuits. Curiously, the intensity of such stray currents increases with depth; they are almost unnoticeable above 500 feet, but may occur in erratic surges of nearly 1500 millivolts at depths below 1000 feet in a few areas. Where there are no stray earth currents, potential logs made while keeping the well filled with water (sometimes requiring more than 500 gallons per minute during the period of logging) reveal the permeable zones in the water wells (Fig. 8).

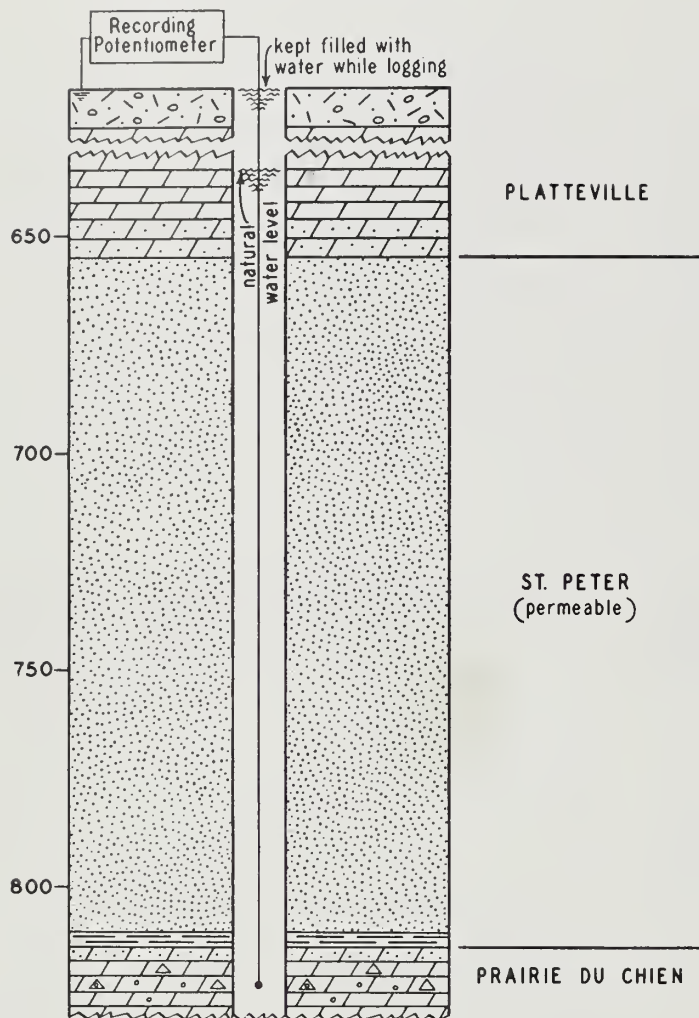
There are several methods of measuring the electric resistivity or impedance of the formations in a well. That most commonly used is similar to the method of measuring earth-resistivity at the surface except that the potential electrodes and one of the current electrodes are combined in a traveling assembly which is lowered in the well, and the other current electrode is grounded at the surface. The potential or measuring electrodes are spaced from a few inches apart, for detailed logging of thin-bedded zones, to six feet or more, for deeper penetration of the wallrock. Wide electrode spacing is used to investigate the character of the fluids in the porous formations beyond the zone invaded by fluid from the well bore. Measurements made with closely spaced electrodes sometimes do not penetrate deeply enough into the formations to reveal their true character, and most measurements made with widely spaced electrodes fail to show thin beds.

Another method, and one which provides extremely detailed logs of thin-bedded zones, employs a single traveling electrode and one electrode grounded at the surface.

In all methods the resistivity measurements are affected by the character of the fluid in the well bore and by the hole diameter, as well as by the character of the wall rocks and the fluids in them.

On most well surveys two or more electric resistivity logs are run, usually the "normal" curve made with the potential electrodes closely spaced (ordinarily 18 inches apart) or with the single traveling electrode to obtain a detailed log, and the "third" curve made with the potential electrodes from four to six feet apart to obtain information concerning the fluids in the formations. Where further information is needed, additional logs can be run with the potential electrodes only a few inches apart (the "auxiliary" curve) or more than six feet apart (the "lateral" or "fourth" curve).

# MEASUREMENT OF ELECTRIC POTENTIAL UNDER INCREASED HEAD



# PORTIONS OF POTENTIAL LOGS OF A WELL IN NORTHEASTERN ILLINOIS

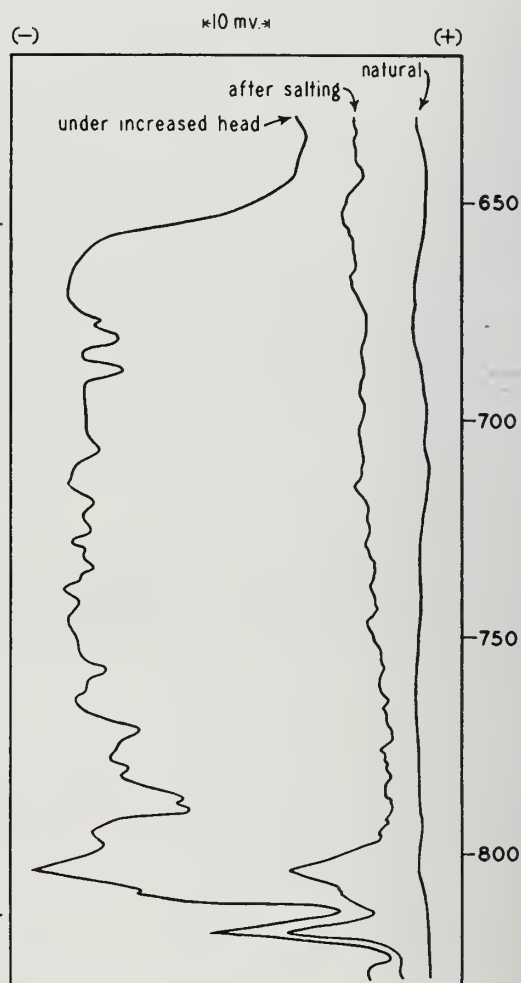


FIGURE 8.

Electric potential logs recorded under different conditions to locate permeable zones.

The resistivity curves are used primarily to log the lithology of the wallrock in wells, but from them the character of the fluids (fresh water, salt water, oil, gas) can be surmised, and the exact location of casing and liner in the hole can be determined. Non-porous non-argillaceous materials, such as most limestones and dolomites, have high resistivity values; shales and other argillaceous materials have low resistivity values; the resistivity values of porous rocks such as most sandstones and some dolomites and limestones depend largely upon the amount and character of the contained fluids, and generally are intermediate between the typically high values of limestone and the low values of shale. The resistivity of metallic objects such as casing is extremely low. Close correlation of well-cuttings and resistivity curves in a number of wells gives a sound basis for

interpretation of the curves for nearby wells for which well-cuttings are not available.

In the writers' experience the stray earth currents have not interfered with the measurement of electric resistivity or impedance in wells, probably because all such measurements have been made with pulsated direct current or alternating current. In one exceptional case, where pulsated direct current was used, there was interference from a nearby power source in period with the pulsator. After it was recognized, by analysis of the resistivity and potential curves, the rate of the pulsator was increased and no more disturbance was encountered.

## Fluid Temperatures

Temperature logs record the temperature of water in the well, and from these logs the temperature of

water from the different aquifers may be recognized (Fig. 9). In northeastern Illinois there is a geo-thermal gradient of a 1°F. increase for each 125 feet beginning at a depth between 150 and 300 feet where the temperature is about 50°F. the year around. In only one or two wells has the temperature approached a constant gradient. In most wells surveyed the temperature does not increase at a constant rate, yet the bottom-hole temperature usually is close to the temperature that would be expected for the

depth if the gradient were constant.

Both cold and warm anomalies reflect departures from the normal gradient. Most temperature curves are interpreted as indicating circulation conditions, geological conditions in the well, or producing conditions in adjacent wells at the time of logging. In a few wells, particularly where there has been a slight decrease in temperature with depth for as much as 1200 feet, some of the conditions are not yet satisfactorily explained.

# DIAGRAM OF WELL SURVEYING THERMOMETER

# TEMPERATURE LOGS OF SOME WATER WELLS IN NORTHEASTERN ILLINOIS

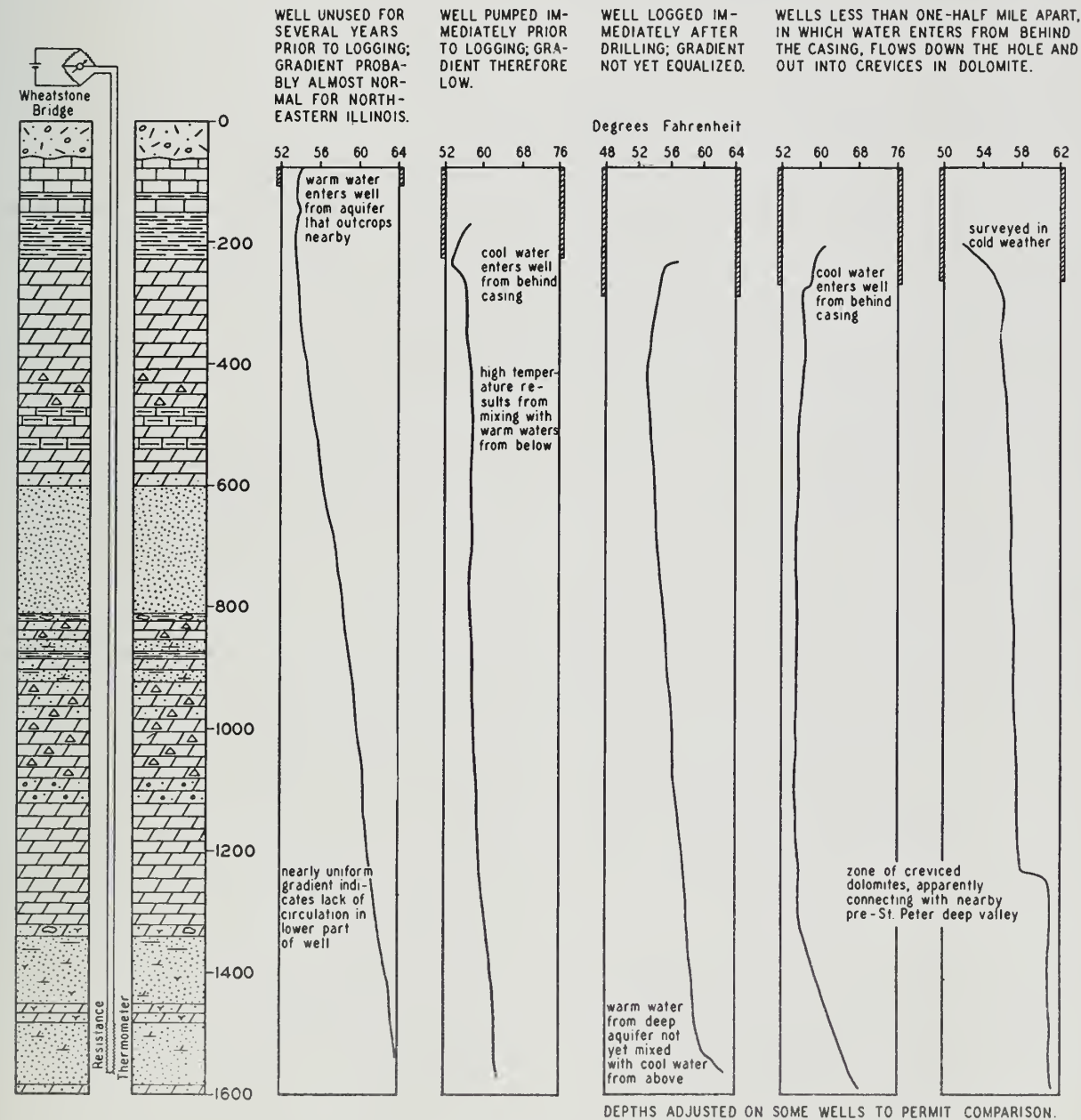


FIGURE 9.  
Temperature surveys of water wells.

The principal use of temperature logs in oil wells has been to locate the approximate top of cement behind the casing. The method is based upon the fact that the heat generated during the setting of the cement produces a marked increase in temperature of the fluid within the casing at the top of the cement. Temperature logs have been used for the same purpose in a few water wells and undoubtedly will be so used to a greater extent in the future, because the advantages of cemented casing are now recognized, and more and more casing strings are being cemented.

In one well a temperature log was run while water was flowed into the well from the surface. From the log the zone where most of the added water was leaving the hole was recognized and thus identified as the principal aquifer.

Temperature logs are made with continuously recording resistance thermometers. There is probably some instrumental variation in many wells which may account for some of the inexplicable results. In many of the wells some well surveying thermometers are affected by "noise" or stray earth currents so that many minor variations and irregularities not indicative of temperature changes in the fluid are recorded. These may mask irregularities which are related to actual minor temperature changes. Therefore, in drafting and interpreting temperature logs, particularly in the industrial sections in and near Chicago, such minor variations are eliminated or disregarded.

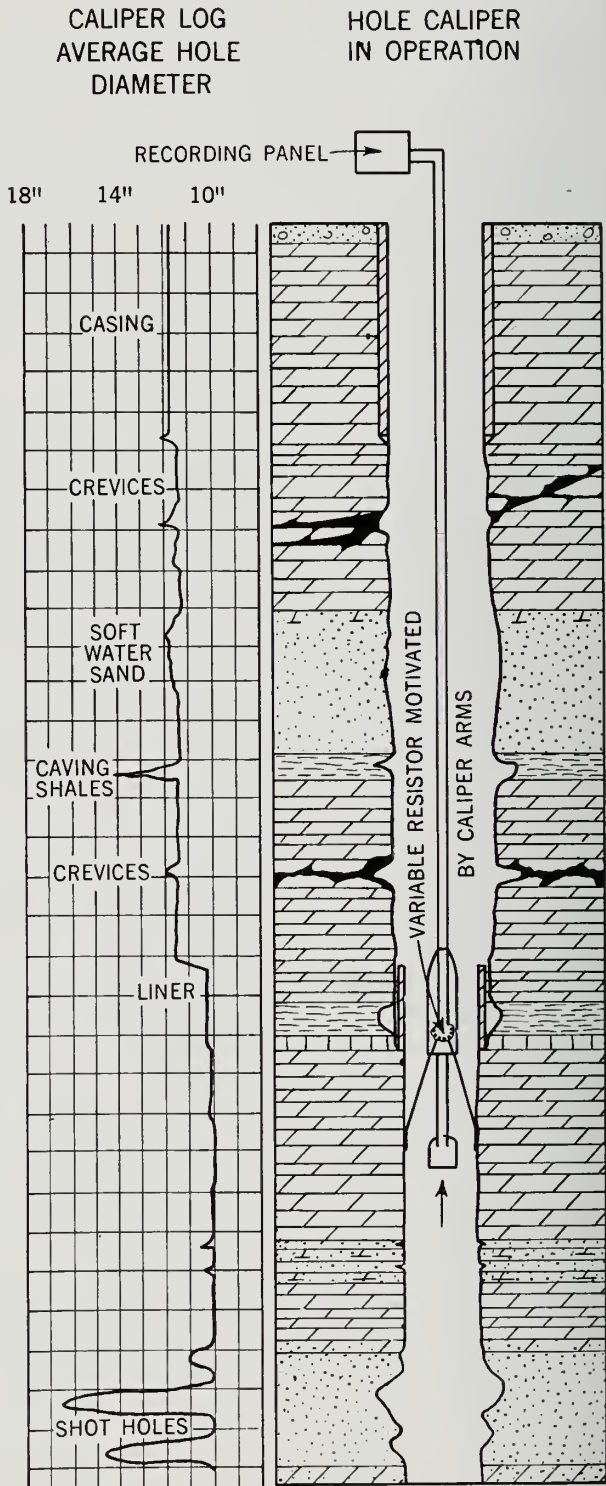
**Hole Diameter**

A continuous record of hole diameter is furnished by the hole caliper (Fig. 10). The caliper tool consists essentially of four arms which are extended by springs, and an electric resistor motivated by the arms. The instrument is run to the bottom of the hole with the arms closed and held to the frame by a small steel band. The arms are opened by breaking the band through detonation of a small shot. Then the average hole diameter is logged as a continuous graph by recording the changes in resistance in the circuit due to the arms moving the resistor as the tool is run up the hole.

Caliper surveys of water wells in Illinois have been valuable in analyzing the effect of shooting, in finding the actual diameter of wells about which there was no available information, and in locating caving zones, as was expected before they were run. They have also furnished additional important information on the condition of casing and liners and

the condition of the casing seat, and have proved the existence of major crevice systems in some of the dolomite formations which, contrary to previous thought, play an important role in the ground-water supplies of northern Illinois.

Caliper records are also affected by stray earth currents in some urban areas, and because these



**FIGURE 10.**  
Caliper survey of water well.

currents cause many anomalies, some of the records are of greater relief than is explained by the variations in hole diameter, especially in lower shaly formations where such interference is at a maximum. Where stray earth currents occur, satisfactory caliper logs have been obtained only by using a rod affixed to the lower part of the tool to break the band and release the arms when the tool is set on bottom, and substituting an A.C. circuit for the regular D.C. circuit to take a series of readings throughout the well.

## Fluid-Resistivity Logs

The logs of the variations in resistivity of the fluid in the well bore have furnished much corroborative evidence regarding circulation conditions within wells (Fig. 11). Fluid-resistivity logs have been

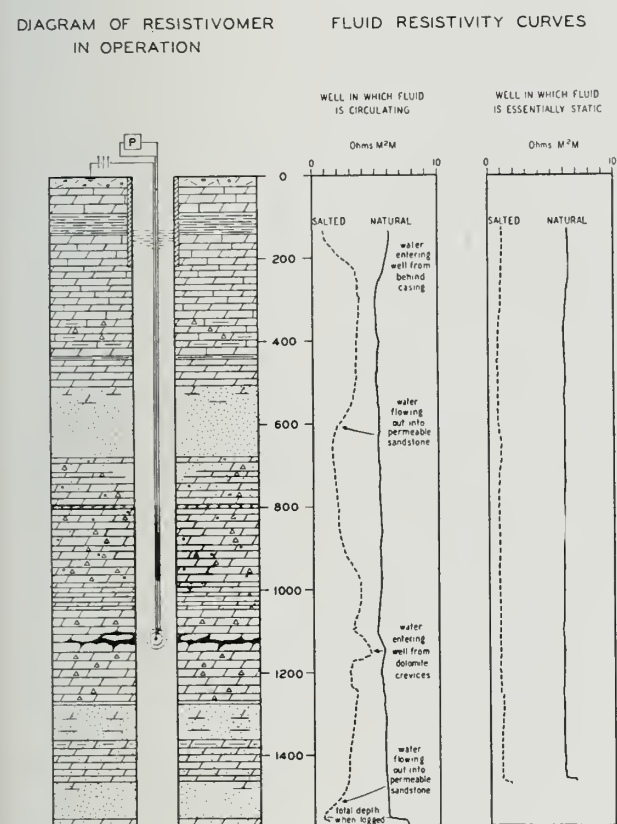


FIGURE 11.  
Fluid resistivity surveys of water wells.

run with several different instruments, all using closely spaced electrodes inside of an insulated tube.

In most of the geophysical surveys made, two fluid-resistivity logs have been run, one under natural conditions and the other after salt was added to the well. Originally it was planned to run a fluid-resistivity survey to check the distribution of salt in the well, and it was decided that in order to do so

it was essential to know what variations, if any, existed before salting. It was found after a few experimental runs that there frequently were major variations in fluid resistivity in wells and that some significance could be attached to them. It was also found that in static wells there was a tendency to spill salt on top of the fluid column while loading the salter so that the top few feet of water were very salty but that otherwise the salt is distributed fairly evenly. However in most of the wells surveyed, the resistivometer surveys run after salting showed even greater variations in fluid resistivity than natural fluid-resistivity curves. Most of these variations correspond to anomalies on other logs and therefore corroborate postulated circulation conditions within wells.

In wells where there is a great change in fluid resistivity at a zone of major temperature change, it is problematical as to whether this change in values actually represents a change in fluid character or whether temperature changes affect the values obtained by the measuring instrument. At present the evidence suggests that actual changes in chemical character of the water do take place at these problematical places in the wells. It is planned to carefully check such instances with detailed water sampling and chemical analyses in the near future.

## Rate and Direction of Fluid Movement

The current meter, modified from the ordinary stream gauging meter, has long been used in water well work. For use in conjunction with geophysical surveys an ordinary stream type propeller meter was adapted to run in a vertical plane inside a protecting housing (Fig. 12). Three contact pins on the gear driven by the propeller are spaced to create signals from which the direction of flow up or down through the instrument can be recognized. The rate of flow can be calculated by timing the period between signals. In using direct current it was found that there was considerable electrolysis of working parts, but satisfactory results have been obtained by use of low amperage alternating current. The chief handicap of this instrument is that it becomes fouled in bacterial growths, debris, cavings, etc., which prevents satisfactory operation.

Another type of current meter has been developed but is still in the experimental stages. It consists of a counter-weighted vane which motivates a variable resistor. Moving fluids deflect the vane upward or downward changing the resistance in the circuit. The instrument is run into a well at a continuous

## CURRENT METER IN OPERATION

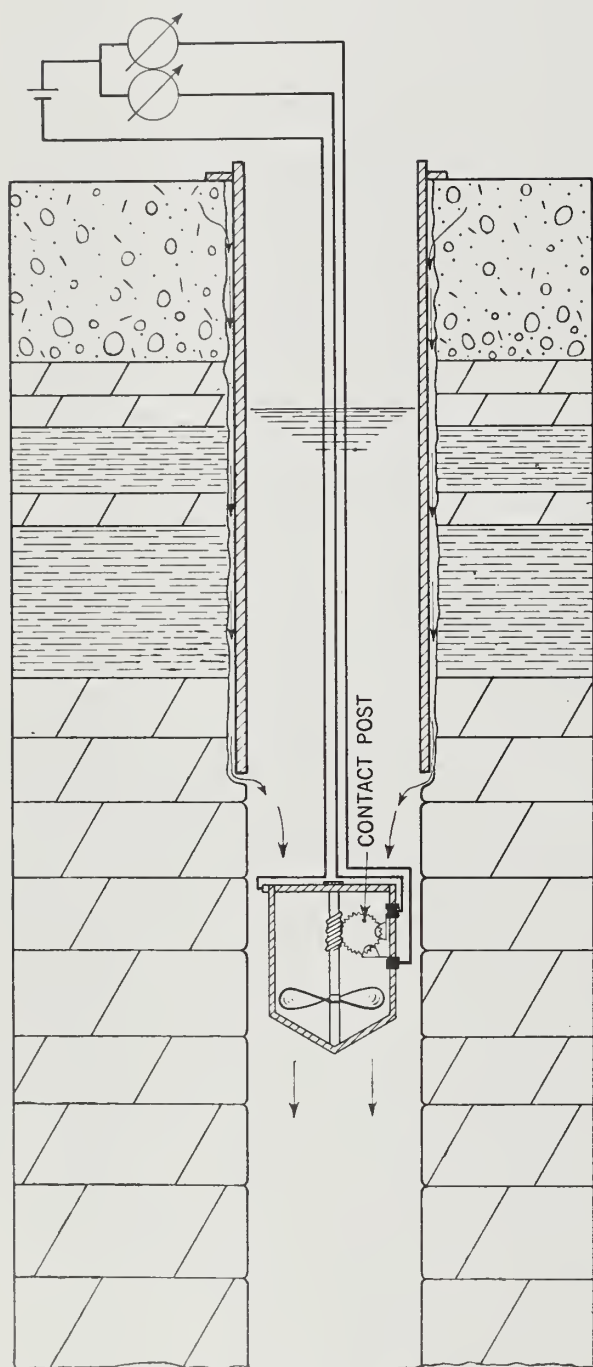


FIGURE 12.

Current meter survey indicating that water enters the well from behind the casing.

rate of speed, giving a known value of deflection, and deviations are interpreted to indicate fluid movement. Experimental calibration of the instrument and trial use in several wells suggest that it may be satisfactory under conditions in which the propeller

type of meter may prove unsatisfactory. A more sensitive model is being constructed and will be tested in the field soon.

## Additional Geophysical Methods for Use In Water Wells

The logs described above have provided much new information and have increased our understanding of ground-water problems in Illinois. There is room for improvement in the technique of operation and in the interpretation of results. A number of other geophysical methods or auxiliary instruments may also be useful in ground-water problems in Illinois and elsewhere.

The formation or drill-stem tester is widely used for testing the fluid content of individual formations in oil wells. To date no formation tests have been run on water wells in Illinois, but valuable information on the water resources has been obtained by the use of this tool in oil wells, and excellent results have been obtained in water wells in other sections of the country<sup>4</sup>. Measurement of the static head or pressure in each aquifer and a sample of its fluid content obtained by use of the formation tester would be worth while for any well.

Various types of fluid samplers, which take samples at different depths, are in use in various industries and fields of investigations. Some samplers have been used in both oil wells and water wells in Illinois but there is no sampler available for use with a logging truck or measuring line which would take samples large enough for chemical analysis. Such a sampler has recently been designed and is to be used in sampling fluids in the well bore in order to obtain more detailed information than is now available and to furnish a check on fluid-resistivity logs.

The camera has been used successfully to inspect the lithology and physical characteristics of the wall-rocks in water wells<sup>5</sup> and is reported to have been used in oil wells. It is believed that use of a camera would be invaluable in fishing jobs and inspecting casing and liners.

Present methods of continuous recording of pH, or hydrogen ion concentration, apparently do not lend themselves readily to measurements at depths such as would be necessary to obtain a pH log of the typical deep water well. However, a pH measuring device is under construction which it is hoped can be adapted to well work and modified to use through the recording panel of the regular logging truck.

The studies should give important information on the chemistry of ground-water, conditions underground, and possibly well equipment corrosion.

Magnetic logging to determine the location of pipe and tools, etc., in wells has not been done on any water wells in the Illinois area as yet. It is expected that some situation will arise to permit the use of this method and a study of its application to the drilling, production, and completion problems of ground-water geology.

Radioactivity surveys (gamma ray and neutron) are used to log formations in cased and uncased portions of oil wells. It seems likely that these methods of investigation, particularly as applied to the formations behind the casing, should prove useful in some water well problems. For instance, it may permit the identification of both glacial and bedrock aquifers which have been cased off, thereby giving new information from existing wells.

Attempts have been made with one of the available side-wall samplers or coring devices to obtain samples of the wallrock of an Illinois water well for core analysis and study. It is believed that valuable information on wells already drilled and on formations which do not crop out close to the producing areas may be obtained from such side-wall samples, but most of the wallrock in the deep wells of Illinois is too hard to be sampled by the methods hitherto available. Recently developed side-wall sampling devices may prove successful.

### **Water Well Problems Clarified by Geophysical Logging**

Many problems arise in drilling, completing, and producing water wells. The data needed for the solution of some of the problems can be supplied by subsurface geophysical methods, but the geophysical evidence of subsurface conditions is largely indirect so that for sound interpretation of the data more than one line of evidence bearing on any problem is desirable. In many instances the geophysical data must be supplemented by some knowledge of the subsurface geological conditions.

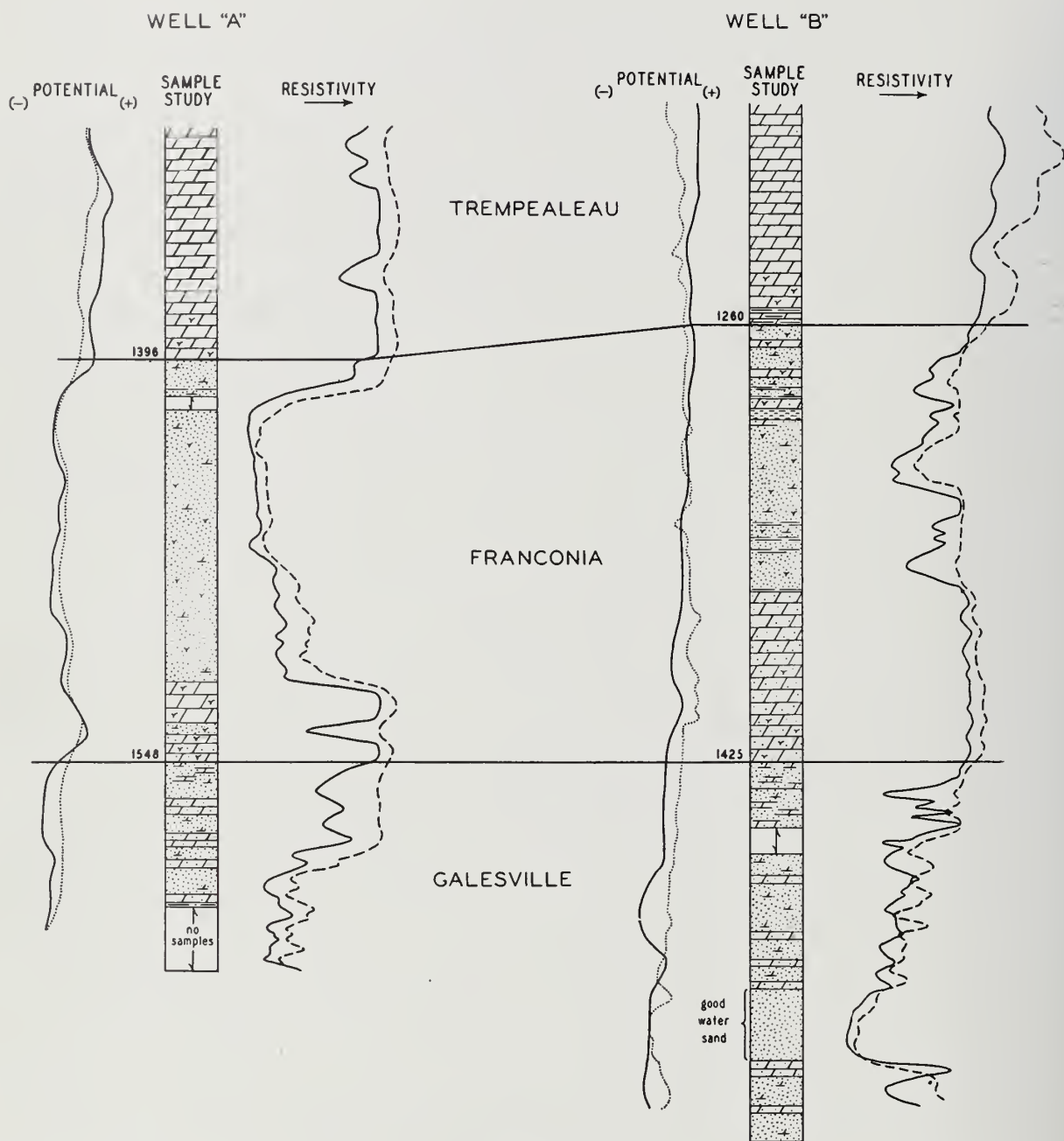
In wells that produce from several zones, as do most of the deep wells in northern Illinois, it is desirable and in many cases essential to know the depths and thicknesses of all the water producing zones, the amount, quality, and temperature of water produced from each, and the differences between the hydrostatic heads of different zones. Most of this

information could be secured during the drilling of the wells if extreme care were used to observe and record the action of the drilling tools, the character of the cuttings, changes in composition and volume of fluid in the well, and if each possible producing zone were separately tested with the formation tester or by pumping. Unfortunately these precautions are seldom taken so that for too many wells, particularly those drilled some years ago, little is known other than that they are holes in the ground of a certain diameter at the top. If the yield is insufficient, or if the quality or temperature of the water is undesirable, detailed data on the subsurface conditions are needed so that the well can be worked over intelligently and economically in order to get the desired quantity and type of water. The zones that should be cased off, casing and liners that should be lowered or replaced or cemented, zones that merit shooting or acidizing, and all of the other conditions within the well that affect its production must be recognized. Most of those conditions can be determined from geophysical logs of the well. Thus one of the most important contributions of geophysical surveying has been that of supplying as complete information as possible on old wells as a guide to working them over.

In some cases the question arises as to whether or not deepening a well will increase the supply of water, and if so, whether or not those deeper supplies will be of usable mineral content and temperature. Correlations with other wells (Fig. 13) based on electric logs and the determination of geothermal gradients from temperature surveys afford good bases for estimates of conditions at greater depths in any well. Figure 13 shows logs of two wells that are about five miles apart. The yield of well A was disappointingly low although it was reported to have been drilled through the Galesville sandstone, the principal aquifer of the region. No cuttings were available from the lower part of the well, however, so the report could not be checked geologically. Other geophysical surveys in the area had demonstrated that only the lower portion of the Galesville sandstone is permeable enough to produce much water, although an examination of the well-cuttings would lead one to think that the whole thickness of 140 to 200 feet is good water sand. The productive portion of the Galesville is marked on electric logs by homogeneously low resistivity values. Correlation of the log of well A with that of well B, which was known from study of the cuttings to have been drilled through the Galesville and into the underlying formation, shows that well A was not drilled deep enough to reach the good water sand. Deepen-

ing of well A only 50 feet may be expected to greatly increase its yield, and on the basis of temperature logs and fluid-resistivity measurements

made in other wells in that area, it is thought that the additional supplies of water will be of desirable quality.



**FIGURE 13.**  
Correlation of portions of two wells by electric logs. Well A does not reach the good water sand penetrated by well B.

Where considerable differences in hydrostatic head exist in the various aquifers of multizone wells, some zones may take or "thieve" water from the wells. By use of temperature logs, fluid resistivity logs, and current meter logs in conjunction with the electric log such thieving zones can be recognized (Fig. 14). If the thieving zone is a creviced dolomite, as

it frequently is in Illinois wells, the caliper log also is helpful in locating it.

In the well illustrated in figure 14, large changes in fluid resistivity and temperature at the creviced zone indicated on the caliper log coincide with a major disturbance of the potential curve of such

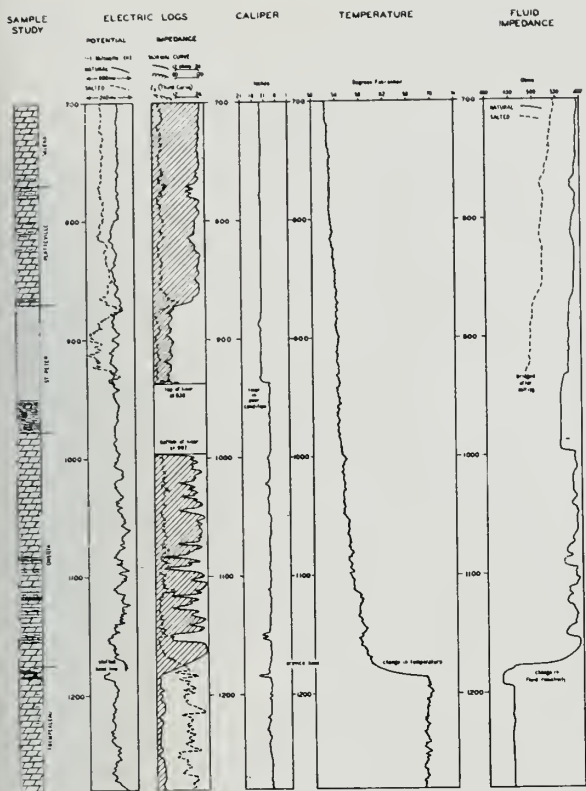


FIGURE 14.

Portion of a composite geophysical log of an industrial well in Chicago showing the influence of a crevice zone.

magnitude that it was necessary to introduce a manual shift to keep the record on scale in spite of the fact that full scale is 900 millivolts. The relations of the curves suggest that large volumes of water were leaving the hole through these crevices at the time of logging. When the head on such thieving zones is lower than the operating levels in the well it is desirable to shut off the zones and thus increase the yield of the well.

The location of casing and liners in a well and the determination of their condition is an important problem. In figure 14, the impedance curve showed a liner from 938 to 997 feet, and the irregularities in diameter measured by the caliper indicated it to be in very poor condition. For the well in Figure 15 there was an old set of samples but no reliable record of the pipe or of the hole diameter below the top. The length of the casing and the position of the top of a liner were determined from the impedance log, and the diameters of the casing and of the open hole were measured with the caliper. The hole was bridged across the liner at 740 feet so the log could not be run deeper. This well was being used as an observation well, supposedly to record the fluctuations in water levels as indicative of the water resources of the important sandstone aquifer at about

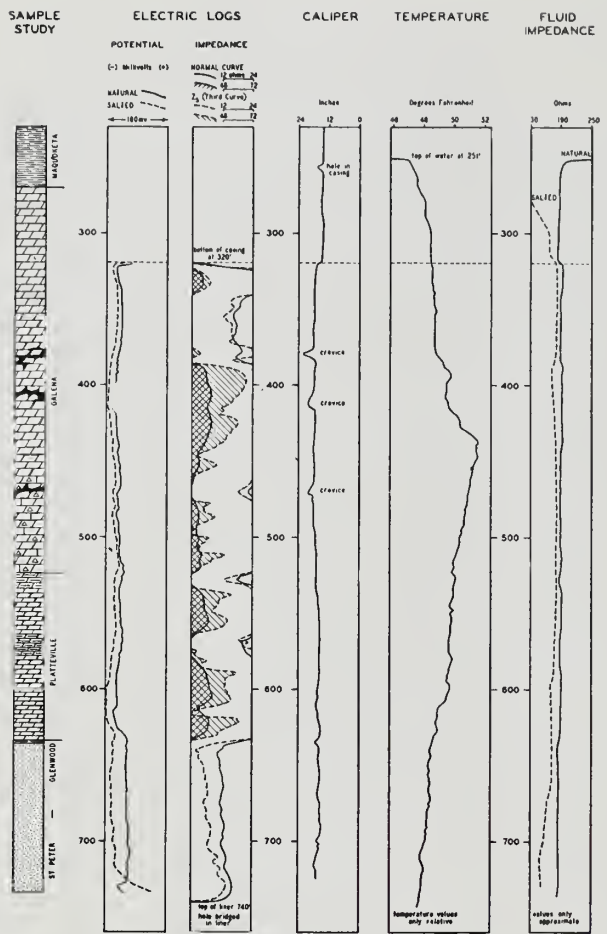


FIGURE 15.

Composite geophysical log of an abandoned municipal well in northern Illinois.

1600 feet through which the well was reported to have been drilled. The geophysical survey, by indicating that the hole was bridged, showed that the water levels could reflect hydrologic conditions only in formations above 740 feet. In addition a hole in the surface string of casing was located by the caliper at a depth between 250 and 260 feet. As the well was logged in the middle of the winter during its period of highest water level, and the top of the fluid, as indicated by the temperature and fluid-resistivity curves, so closely coincides with the hole in the casing, it appears that the water levels are controlled by the rate at which water can leave the well through the hole. It became apparent that this well was valueless as an observation well for water level data.

Some wells are polluted or contaminated by surface or near surface waters that enter through holes in the casing, through crevices in the rock below the casing, or from behind an imperfect casing seat (Fig. 16). By using either temperature, current meter, or fluid-resistivity surveys or all of them in

conjunction with electric logs and caliper logs, the place of entrance of such waters can usually be determined. With that information the proper remedial measures such as replacing the defective casing, extending casing below the crevices or poor casing seat, or cementing, can be employed and the pollution or contamination be eliminated.

Water from the well illustrated (Fig. 16) was unfit for use as either drinking water or boiler water in the ordnance plant by which it was urgently needed.

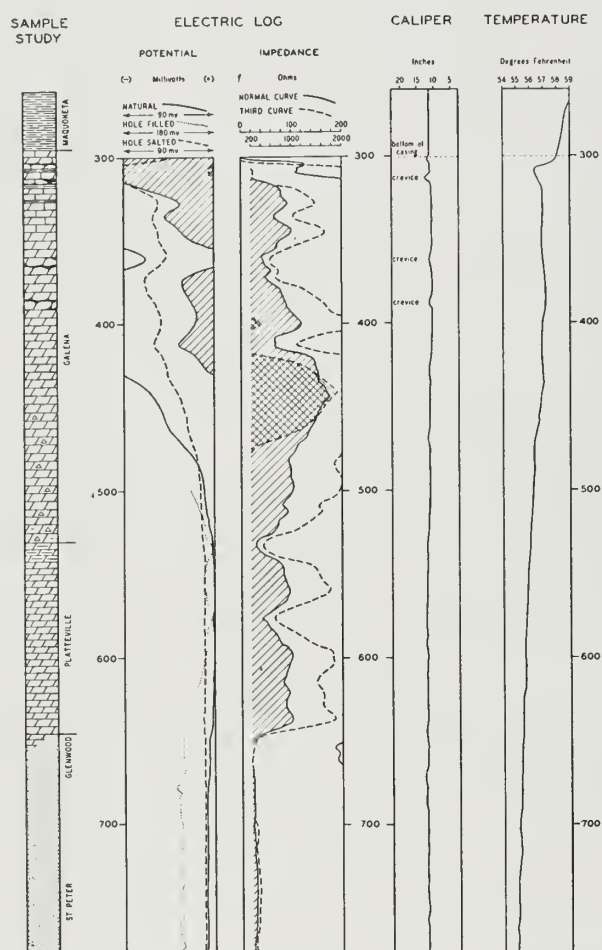


FIGURE 16.

Portion of a composite geophysical log of an ordnance plant well indicating that the source of contamination and pollution is water from near-surface aquifers that enter the well around the casing shoe.

The position of the casing seat was located by the electric log and the caliper log. A 120-foot section of the dolomite below the casing was shown to be creviced, but the high negative potentials indicated that water was leaving the hole through the crevices. A distinct "cold" anomaly was recorded on the temperature log just below the casing seat, and inasmuch as the well was surveyed in warm weather and the fluid column in the casing was warm this anomaly

was interpreted to mean that cold water from behind the pipe was entering the well around the casing seat. When the current meter was spotted just below the pipe it showed that water was moving downward at a velocity such that the flow was about 200 gallons per minute. On the basis of the geophysical survey it was recommended that the casing be reamed down to a firm seat below the upper crevice zones and cemented to the top. All of the pollution and contamination was shut off by this re-working. The water from the well had been extremely variable in composition and had necessitated considerable expense in treatment. By shutting off harder waters from the glacial drift and the surface waters, a water of constant composition was obtained and treatment costs were greatly reduced.

For better drilling and completion practice it has been worth while to analyze the effect of shooting sandstone zones in wells (Fig. 17). A number of 150-pound shots were used in different spots in a northern Illinois well without knowing exactly where the producing water sands were. In the good water sands the diameter was enlarged from 12 inches to 32 inches but in the tight sands the maximum diameter obtained was 20 inches.

Caliper logs are valuable aids to reworking old wells because they locate tight spots and zones of caving shales, conglomerate, or soft sandstones in the wells. The caving shale and conglomerate at a depth of about 460 feet in the well shown in figure 17 probably should have been cased off during drilling. The "tight spot" or place that was not drilled to gauge between 980 and 990 feet should be reamed out to allow free movement of tools while working on the well and to prevent subsequent bridging by caving materials which would shut off the water sand below.

In addition to the location of casing and liners, it may be important to know the location of lost tools or junk in the hole. As has been shown, the electric log gives good measurements of the casing and liners and in some wells (Fig. 18) locates the position of drilling tools, joints of old air-lift pipe, and other steel or iron articles that might have been dropped in the hole. In the bottom of the well illustrated in figure 18 the portion of a string of tools lost while cleaning-out after shooting was located by both the electric log and the caliper log. Inasmuch as they were below the shot-hole in the main producing water sand and it is unlikely that the well will ever be deepened they were not fished out. The shot-holes in this well also illustrate clearly the differences in

the effects of shooting the loose water sand and the tight dolomitic sand.

Although not common in Illinois, there are areas where fresh-water sands are interbedded with sands that carry salt water. The salt-water sands can be differentiated from the fresh-water sands by the resistivity curves of the electric logs or by production tests with the formation tester. Such work has been done in the Houston, Texas, area<sup>6</sup> and deserves wider application. In an oil-test well in Illinois in an area where additional water resources are needed a fresh-water sand below salt-water sands was identified by an electric log and a drill-stem test. Further work is needed to indicate whether this will be a worth while discovery, but at least it has indicated that valuable information on ground-water resources may be obtained from an analysis of the electric log data from the thousands of oil wells drilled in the state.

A byproduct of the geophysical well surveys is the location of areas and subsurface zones in which stray electric currents are most intense. These stray

currents probably account for much of the corrosion of liners, casing, pumps, and column pipe in wells, especially in industrial districts. Geophysical methods have long been used in the study and remedy of electrolysis and corrosion of pipelines, underground telephone and telegraph cables, and other buried metal objects. It is hoped that as additional data on stray electric currents and their relation to corrosion are collected by geophysical surveys and other methods, some practical suggestions toward the solution of these problems in wells can be made.

Integration of Geophysical and Geological Data

Through compilation and comparison of geophysical data derived from a number of methods of investigation, supplemented with all available geological and production data from the well in question and nearby wells, a reasonably good picture of subsurface conditions can be obtained and many of the problems of ground-water production can be solved. To integrate all such information, a composite log of each well is prepared on which is displayed all the phases that have been investigated

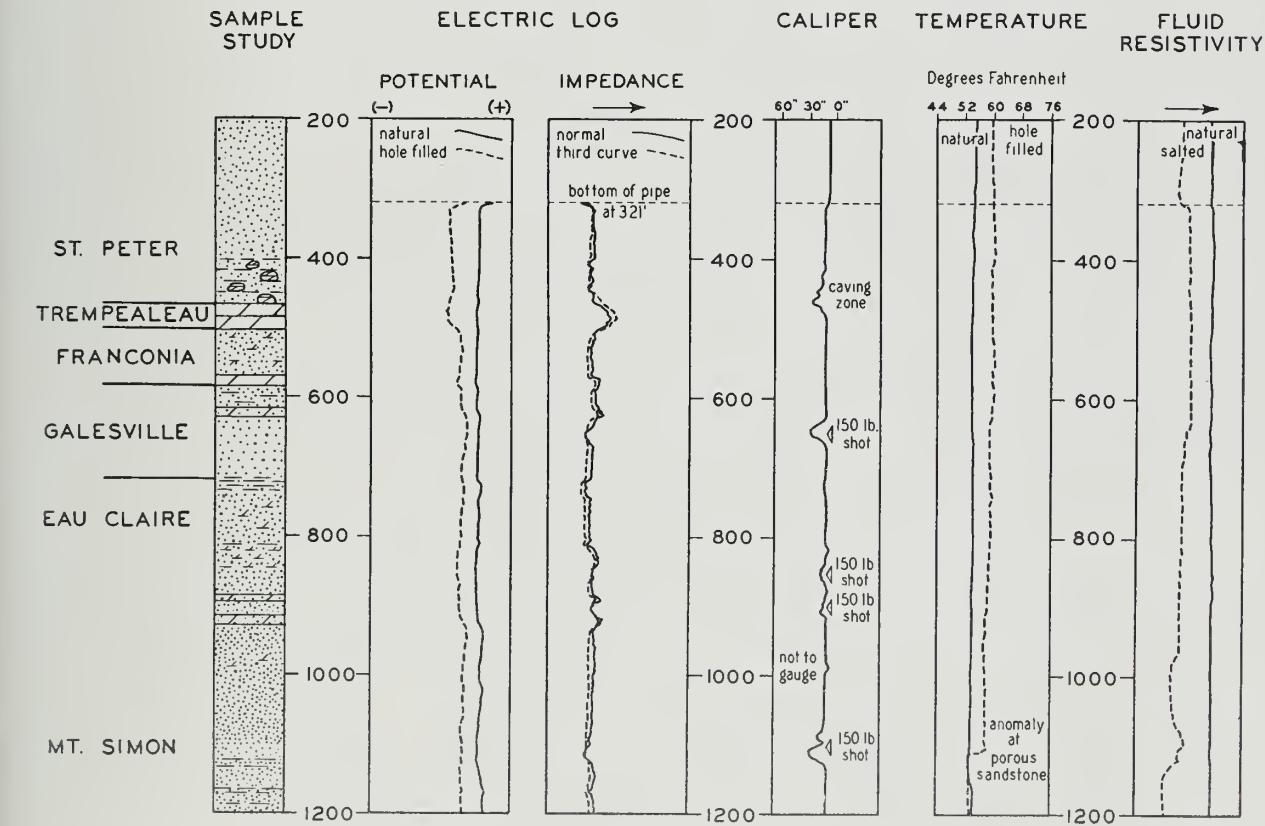


FIGURE 17. Portion of composite geophysical log of a municipal water well. The caliper log shows the effect of shooting and caving on different zones. The temperature log made with the hole filled with water shows the location of an important permeable zone in the Mt. Simon sandstone.

(Fig. 19). The composite logs now made by the Illinois Geological Survey present data that form the basis for the following:

1. A detailed log of the lithology of the uncased portion of well based on microscopic study
2. Exact measurements of the casing and liners, both as to depths and inside diameters, and some knowledge of their condition.

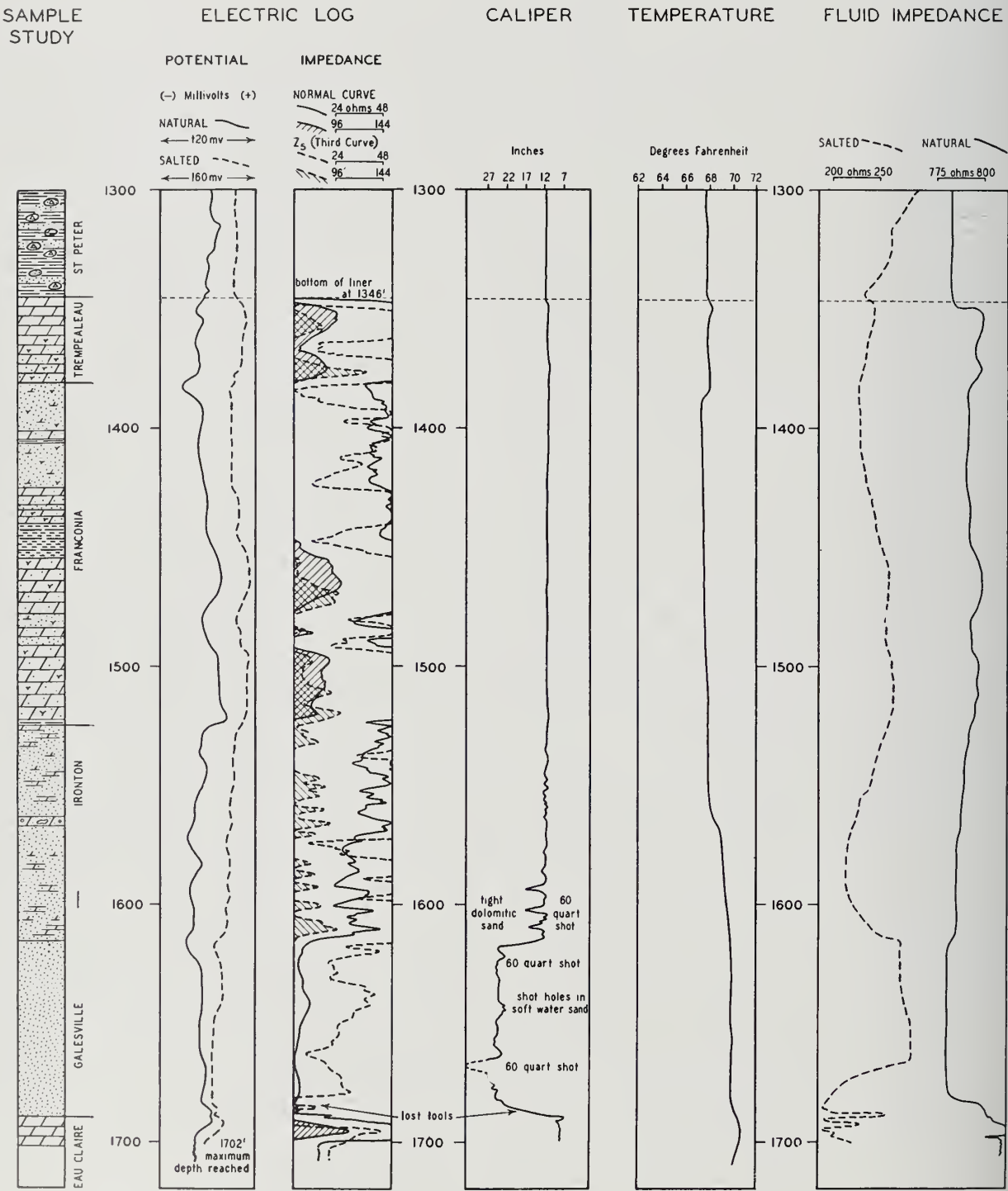


FIGURE 18.

Portion of a composite geophysical log of an ordnance plant well showing the location of bottom of liner and lost tools and the comparative effect of shooting on soft water sand and tight dolomitic sand.

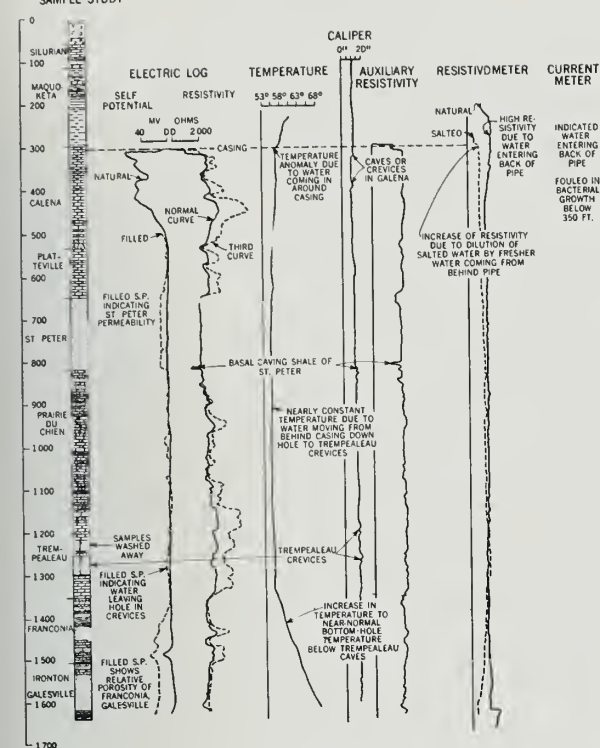


FIGURE 19.  
Composite geophysical log.

3. Location, thickness, and relative importance of the water-producing zones.
4. Location of "thieving" zones.
5. Approximate salinity of the water in the well bore, and probable zones of production of waters of different salinities.
6. Temperature of the water in the well bore and the approximate temperature of water from different zones.
7. Caving zones that have not been cased off.
8. Circulation conditions under nonoperating conditions.
9. Critical production or well conditions such as collapsed or corroded liners, poor casing seats, location of iron or steel "fish," etc.
10. Effects of shooting, acidizing, caving, and other special conditions within the well.

### Summary

In summary, geophysical methods have proved successful in locating ground-water supplies and in solving many of the problems that arise in drilling, completing, and producing water wells. The geophysical surveys made of Illinois water wells and research in ground-water geology have furnished much factual material that, when properly integrated,

usually permits sound interpretation of ground-water phenomena and subsurface conditions. Such knowledge can be used for remedying many of the defects in old wells and for planning more intelligent development of ground-water resources in the future.

As the investigations are continued it is expected that many of the questions in geophysical surveys and interpretations will be answered, and that new techniques and instruments can be developed for solving other problems in ground-water work, not only in Illinois but in the many other areas where the same or similar problems are encountered.

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### PREPARED DISCUSSION

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**Mr. N. A. Rose:**

This paper is a timely one and is of great interest to me. It should prove particularly helpful to ground-water hydrologists working in areas of similar geologic conditions. The authors present a real contribution to the bibliography of ground-water. I agree heartily with the suggestion that ground-water hydrologists should take full advantage of new developments in other scientific and industrial fields. Each new adaptation is another tool that will aid in solving ground-water problems. The Ground-Water Division of the Federal Geological Survey has used many of the "geophysical methods" in ground-water investigations throughout the country, but I do not know of any one study that has incorporated as many methods as this Illinois study. I wonder if the complete "geophysical log" has been adopted as standard practice in future ground-water studies in Illinois and whether the data obtained from all of the surveys justify the cost. It would be interesting to see a comparison of the cost and the relative amount of information obtained from each survey.

In the discussion of electrical logging the authors state: "By measuring the potentials under different conditions . . . some idea of the relative permeability of the different formations can be obtained." This statement is rather optimistic in view of the results obtained by petroleum and ground-water investigations in the Gulf Coast region, which show that no quantitative determination of permeability can be made by potential measurements. The chief function of the potential curve in ground-water studies in the Gulf Coast region has been to determine the approximate chloride content of the water contained in the sands penetrated. Positive values opposite the sands show that the chemical character of the water in the sand is probably better than that contained in the drilling mud and conversely, negative values opposite sands show that the water in the sands is probably poorer in quality. Thus, the chloride content of the water in the sands can be estimated if the chloride content of the water used in the drilling mud is known. In a test well at Houston, Texas, the chloride of the water in the sands penetrated ranged from 40 to 650 parts per million and the chloride in the water used in the drilling mud was about 250 parts per million. The values of the potential curve opposite the sands were positive from the surface to a depth of 1,335 feet and negative from 1,335 to 1,526 feet, the bottom of the hole. A water sample from the sand at 1,400-1,415 feet showed a chloride content of 215 parts per million, thus the potential values changed from positive to negative

when the chloride content of the water in the sands and the water in the drilling mud were approximately the same. It is recognized that the potential curve results from a number of causes, however, it seems that the governing factor in this case was the solution-concentration differences.

On page 8 the authors state that "In all methods the resistivity measurements are affected by the character of the fluid in the well bore and the hole diameter as well as by the character of the wall rocks and the fluid in them." It seems that this should be qualified by stating that the amount of the effect caused by the fluid in the well bore and the diameter of the hole is dependent upon the electrode spacing. The effect increases as the electrode spacing decreases.

The authors' classification of resistivity values on page 9 might be made clearer by setting forth the basic factor that governs the electrical resistivity of rocks: the resistance of a rock to the passage of an electric current is not dependent upon the mineralogic make-up of the rock but on its physical characteristics and the solutions it contains. In general high resistivity values are recorded in dense, compact rocks like limestone, coal and rock salt and in permeable formations that contain fresh water, oil or gas as their interstitial fluid. Low resistivity values are recorded in permeable formations that contain in their interstices saline water and in non-permeable formations, such as shales and clays, which usually contain mineralized water in their minute pore spaces.

In urban areas in the Gulf Coast region results similar to those of the writers have been experienced in respect to the effect of spurious and stray earth currents on the recording of the potential curve. In such cases the potential curve has been valueless.

The subtitle "Hole diameter" is given on page 11. It seems that Caliper surveys, which is used in the discussion, would be a more appropriate title for this section. To the average reader "hole diameter" means the size of the bits used in drilling the hole.

The authors mention the use of electrical logs of oil tests as a possible source of information on ground-water resources. The Ground-Water Division of the Federal Geological Survey in Texas has taken full advantage of these valuable data. The logs have been used to determine the thickness, extent and position of water-bearing strata and the approximate depth to water of high mineral content,

and to correlate important aquifers in local and regional studies. The oil companies and electrical logging companies have shown a sincere interest in the ground-water investigations and have made electrical logs available for this work.

The drill-stem tester has been frequently used in exploratory water-well drilling in the Gulf Coast region. Up to the present time the use of electrical logs in conjunction with drill-stem samples and drilling-mud data has proved to be the most valuable "geophysical method" used in ground-water investigations in this region.

**Dr. Parke A. Dickey:**

In Mr. Bays' paper he modestly acknowledges the contribution to ground-water problems of techniques developed in the petroleum industry. After reading his paper I am inclined to believe that he and his associates will repay with interest any debt they may owe the petroleum geologists. I can see immediate applications of some of the methods developed in ground-water work to oil production; especially to that branch in which water is used to expel the oil from the sand.

As one whose principal concern is oil wells, I have been interested to compare the differences in application of electrical techniques to oil and water wells. The features of oil-well electric logs are mainly due to the presence of brines in the sands and shales. In freshwater strata the salts are lacking; probably washed out by circulating meteoric waters. Dr. Bays has ingeniously introduced salt into the well water to bring out certain potential and resistance features which otherwise are not present. It is interesting to note that salt water in the drill hole of an oil well makes it difficult or impossible to get a readable curve. The cause of the natural potentials is not yet understood, but it is becoming clear that they depend in large part on the salt content of the fluids in the hole and in the formations. More interesting comparisons between water-well and oil-well logging could be made, but it seems hardly profitable to do so before the present audience. However, the methods of determining the points of entry and exit of fluids into the hole are in many cases applicable to oil wells, and these methods will undoubtedly have immediate and important applications to petroleum engineering problems.

A point that needs repeated emphasis is that in electrical well logging it is generally not possible to say with assurance that such-and-such a feature is

indicative of such-and-such a condition. In the early days of oil-well logging it was found that an oil-bearing sand was usually associated with a high negative potential combined with a high resistance value. It was forthwith assumed that these features always indicated an oil sand; and that conversely, where they were absent no oil sand was present. Only at the cost of much grief and expense was it found that this was not always the case, and that very misleading results ensued from simple, rule-of-thumb interpretations. Sometimes the disillusionment was so intense that electric logs were dropped in spite of the valuable information that they did give. Any electric log should be interpreted in the light of previous comparisons with cores and samples in the same area, and with as complete as possible a knowledge of the hydrostatic conditions in the hole. The fact that in ground-water work eight or nine curves combined with a lot of geological and hydrostatic data are necessary, should not discourage the advocates of this method. The very fact that the curves are not as simple as those from oil wells may prevent the misinterpretations and misunderstandings that have attended the use of electrical logs in the oil industry.

It is because of my caution and desire not to read more from the curves than they show, that I am tempted to quibble a little about the use of the term "resistivity." It is customary, as in Dr. Bays' paper, to use this word to mean both the specific electrical resistance of the rocks and fluids, and also to describe the electric log curve which is chiefly affected by these resistivities. The former usage is correct, but the latter is not. As Dr. Bays is probably himself fully aware, the values called "resistivity" in some of his illustrations are not really true values of the resistivity of the rocks or fluids, but really resistances as measured in values proportional to ohms. They may be called apparent resistivities. The only condition whereby apparent resistivity is equal to true resistivity is when both the fluids in the bore hole and the rocks, for a large distance around the electrodes, have precisely the same resistivity. This seldom or never exists, and at all other times the values depend on the electrode spacing, configuration, and the diameter of the bore hole. In some of the illustrations the resistance curve is called "impedance in ohms," which is correct, as alternating current was doubtless used in most of the measurements.

It seems to me that work of this sort by a State organization is not only proper but to be commended very highly. The average water well driller or user has neither the engineering background nor resources

to develop these techniques himself. Their development and use will, however, directly and materially benefit all the users of well water, who, I imagine, include every man, woman, and child in the State. I am inclined to think that the work described in this paper may prove to be of greater utility and benefit to humanity than the application of geophysics to petroleum, useful as that has been.

**Mr. E. W. Bennison:**

The writer feels somewhat hesitant in attempting a discussion of this very excellent paper for the reason that he knows so little about the subject of geophysics, having spent more time on the development of ground-water by the methods in general use. Therefore, this paper describing the progress that has been made in the application of geophysical methods to ground development is practically all new information to the writer and of extreme interest.

For many years engineers, public officials, well drilling contractors and others have heard of geophysical testing in the oil well field and no doubt have speculated on the use of such methods in the ground-water field. Unfortunately such literature as there is on the subject of geophysics is too complicated and theoretical for general understanding much less use in the field of ground-water. Dr. Bays' paper therefore is especially valuable for it not only gives us an insight into what has been done but what can be done toward the practical application of geophysical methods in ground-water problems. It gives the information in such a way that we can understand it and make use of it.

The value of ground-water cannot be calculated as being so many dollars or cents a barrel like oil, therefore its value is not appreciated or considered until one is without it. When we look around us and note the thousands of dollars that have been spent in attempting to locate and develop ground-water, when we see important and essential industries rendered useless from lack of ground-water or cities and towns whose development has been hampered by a lack of ground-water, then we have a faint conception of its value but we cannot calculate it. There is no field or phase of modern engineering that has been so neglected or poorly understood as the field of ground-water development. So, when we see geophysics coming into practical use in the ground-water field, we are encouraged to look ahead to the day when these methods will be available to all ground-water users and play a part in every important ground-water development.

In the writer's opinion there is still much to be done, however, before geophysical testing can come into general use, for as Dr. Bays points out, it is still in the experimental stage and at best does not completely answer all of the questions presented in undertaking a ground-water development.

To those familiar with the methods used at present in making ground-water surveys such as surface surveys, geological investigations, test holes, pumping tests, etc., it will be difficult to visualize geophysical methods in general use for some time, for the following reasons:

1. Geophysical investigations require the use of special equipment, too costly for general use. also the use of men highly trained in this sort of work in order to carry out the field work and interpret the results obtained. At present there are only a few organizations who have the men and equipment available and who have had training and experience in the ground-water field. This in itself limits geophysical investigations to those cases where more or less of an emergency exists and there are time, money, trained men and equipment available.

The development of ground-water at present is largely a matter for each individual user, whether public or private, to solve for himself. Very little concern is felt as to the effect of a new development on the general ground-water supply in a given area so long as each individual user can obtain a quantity sufficient for his own needs. The result is that there are in this country several important ground-water areas that are being exhausted rapidly at the present time. Many users of ground-water seeking new or supplemental supplies see no necessity of spending money for putting down test holes, much less using anything as new and costly as geophysics. The needs and benefits of geophysics must therefore be made apparent to the customer whose situation is desperate and who can pay for the service or the service must be available as a public service under the conservation departments or some similar department of the state.

There is no question about the benefits that will be derived from geophysical testing, especially in investigating new areas for ground-water and as Dr. Bays suggests, there are many uses of geophysics that can be made in areas already developed. This brings us to our second question.

2. Assuming that geophysical methods are developed to the point where surveys using these

methods can be made with a minimum of cost and time, then the question arises as to just how much dependence or practical use could be made of the information obtained. In making an actual ground-water development by means of wells, it is not of much help to know that ground-water is available in a given area or location. We must also know the actual depths to rock, the number and location of impervious strata and the location, thickness and permeability of each water-bearing stratum. We must also know the rate of withdrawal and replenishment from the area under consideration. Furthermore, the actual log of the formations must be known in order to determine the proper type of well to construct. In other words, something definite must be known of the actual yielding ability of the water-bearing formations. This information can only be obtained from competent analysis and interpretation of representative formation samples.

Therefore as the writer sees it, geophysical testing will be of great help and assistance in locating ground-water areas, determining their extent and general water-bearing characteristics, but when it comes to actual well location and construction, test holes will still have to be put down to obtain all of the information required, just as is done now. Geophysical work will do away with a lot of guesswork and prospect holes in developing ground-water but it will not determine the permeability of a water-bearing formation which in the last analysis is the key to the success or failure of a ground-water development.

Let us hope that the Illinois State Geological Survey keeps up their investigations and that geophysical methods come into general use in locating, maintaining and conserving a most valuable resource—ground-water.

**Mr. O. F. Ritzmann:**

Dr. Bays' very excellent paper is to be commended. The authors have compared a large number of different types of well logs in the same well and brought this material together in a way which is very helpful in evaluating their various uses and merits. Such information is exactly what the engineer wants to know.

The title of the paper might well be changed somewhat to suggest the fact that such a comparative study of well logging methods has been covered. The title as stated might lead one to think surface geophysics would be more fully discussed. It might

be well therefore to expand somewhat on the authors' brief mention of this phase of the subject.

Reference is made chiefly to the electric method, more specifically to a Gish-Rooney method of surface exploration. The feasibility and success of such work has been demonstrated here, and previously also by other authors. The relatively shallow depths to which it is necessary to work are favorable for the application of this method. It is fast and inexpensive in the field. However, any electrical method is handicapped by the fact that presence or absence of water is not simply correlated with high or low resistivity. Success of the method depends on its intelligent interpretation by the geologist.

One refinement might be called to attention, and may possibly have been used by the authors in making the computations. The simple apparent resistivity obtained as in the authors' Fig. 1 may be quite considerably in error when a series of electrical layers having different conductivities exists in the ground, that is, a simple one to one correspondence between depth of bed and electrode spacing is not always correct. If the apparent resistivity—electrode spacing curve is known close to a well whose electric log is also available then an analysis can be made, and similar curves in the vicinity may be interpreted in a similar manner. However, the unknown introduction of an additional thick layer, due to lensing for instance, may throw the interpretation off considerably. Some improvement can be obtained by correcting the resistivities for larger electrode spacings for the values obtained for smaller spacings. The authors do not indicate whether this was done or not. For a two layer problem such corrections are simple to make, and can be obtained, for instance, from a paper on Potential Distribution by Dr. Muskat in *Physics* for April, 1932 and also other authors.

Perhaps it would also be well to call attention to the fact that the layers of increasing resistivity shown in the middle section of Fig. 1, probably do not exist as such. The apparent resistivity curve for say a simple two layer problem will vary from that of the top layer to that of the bottom layer. Plotting the average or apparent resistivity at a depth corresponding to the electrode spacing for which it was observed is merely a fictitious way of showing the observed data and does not imply that these layers really exist. Such a representation, however, is very useful as the authors indicate.

Another surface method which might find more application in ground-water studies is the seismic method. The authors only mention the method here,

but it has been used extensively in studying proposed foundations and for such small scale problems as, for instance, determining the thickness and properties of beds which are of interest in road building. The seismic velocities are low in unconsolidated materials and are higher in these materials when they are water saturated. The total equipment involved in a geophysical seismograph crew doing petroleum exploration is rather prohibitive here, but for small scale work to shallower depths such an elaborate set-up is not required. Some portable and easily operated seismic outfits have been developed and the method appears to be deserving of more extensive application to small scale problems such as that of locating and tracing buried water sources.

Still another type of study not mentioned by the authors is that of core analysis. Possibly this was not used by the authors because they were dealing mostly with old water wells and cores were not available. Cutting can easily be watched for geological information as drilling progresses. If cores are cut one can make permeability and porosity measurements and can determine the amount and quality of the water content. Furthermore, from the physical characteristics of the water bearing sand or rock one can design a system or network of producing wells which will give the most reliable production and avoid bad effects of water table coning, erosion and silting up of the wells and liners.

#### **Dr. P. D. Krynine:**

The measurable physical mass properties of a rock (such as color, structure, density, porosity, permeability) and also other properties, equally important, although less readily measurable (such as swelling, cohesiveness and electrical properties) are the result of the relationships existing between grains, matrix and cement and the reactions of these items with fluids both pre-existing (connate) and introduced.

A rock has really only two basic, fundamental properties: composition and texture, meaning that a rock is made up of certain constituents (generally minerals) put together in a certain way. Even structure is not quite a primary property, but is rather the reflection of changes—abrupt or gradual, horizontal or vertical—in texture and composition within one formation or between different formations.

In the case of fluid bearing rocks the problem is complicated by the fact that both solid and fluid constituents are present in the same rock, but even then the difference is only one of degree, not of kind.

Composition and texture hence are the primary basic, first order properties which can be directly tested and even directly observed in considerable detail under the microscope. The structure of rock units is a closely following derivative.

All the other mass properties of a rock or a series of rocks are derived second or third order properties which can be compared with reflections in a mirror of an object which is not directly seen. The mirror may be straight or it may be a highly distorting trick mirror.

Physical and geophysical measurements are concerned with these second or third order properties. Sometimes the measurements are direct (density, porosity), sometimes they are highly indirect and distorted (permeability on the basis of electrical logging).

In the latter case indeed we are not measuring a property itself but rather what we surmise is the mirror reflection of this property.

The electric log is a perfect illustration. It does not determine the name of the formation, or even its porosity and permeability, but only the formation reactions to the passing of electric currents. These reactions are surmised (*and only surmised!*) to be dependent upon some of the basic properties or closely related second order derived properties (porosity, permeability).

So long as these limitations are kept in mind all geophysical instruments and techniques are highly valuable tools of geologic thought. We must however remember at all times that neither electric logs, nor other geophysical methods give any *direct* geologic or petrologic results, but only a series of numbers on a dial which are in need of skilled interpretation.

If indeed the statement is made that the electric log (or any other geophysical instrument) shows that the highly permeable Big Wolf sand is present in such and such a well at so many feet, this simply is not so. The recording dial does not show the presence of the Big Wolf sand, or even of a highly permeable sand. It shows only a figure, let us say the number 16.

But this reading of 16 can be arrived at in a multiplicity of ways. Indeed you can square 4, or multiply 3.2 by 5, or extract the cube root of 4096, or add 13 and 3. There is almost an infinite number

of textural and composition combinations which may give the same, or almost the same reaction on the recording dial of a geophysical instrument. One of these combinations may correspond to the properties of the Big Wolf, but the others will not. Which one have we got? This question cannot be answered properly without using much geologic—or rather petrologic—background. This background may be local, empirically derived or it may be fundamental, based on a study of primary petrographic properties of rock types in general. The first type of background is frequently found among good field men, but the second type is as yet practically non-existent.

However further advances in the usefulness of geophysical tools must be based upon a correct understanding of the relations existing between the mirrored reflections (possibly distorted 3, 4 or 5 times) observed on the dials of the geophysical instruments and the basic rock properties which cause these figures to appear on the dials.

An intelligent and efficient interpretation of geophysical measurements and a proper understanding of second, third and fourth order parameters is impossible without a proper understanding of the petrographic picture of the rocks involved.

In the case of oil wells and water wells this petrographic picture is furthermore complicated by the fact that some of the constituents of the rock are fluid and that they react with the surfaces of the solid constituents. Hence in oil and water sands surface phenomena are extremely important. But the solids which line the wall areas of pores and capillaries are not necessarily the most important or the most conspicuous ones of the rock. It is entirely possible to have a very "clean" highly quartzose sand consisting of 90% or more of quartz and only 2% of "clay" in which over 60% of the grain surfaces are lined with thin coatings of clay minerals or finely comminuted micas.

These phenomena may be compared to the relationship existing between wallpaper and the other construction materials used in building a house. Only a few pounds of wallpaper are used against tons of brick, cement and plaster, but most of the visible surfaces inside of the house are wallpaper, not brick.

These surface relationships which are of paramount importance in establishing the relationship of fluids to solid inside of porous media have been unfortunately, up to the present, hardly ever studied

at all. Since in addition a considerable amount of the finer grained surface clay linings of pores are not inert, but highly active and can easily react with fluids it follows that the physical mass properties of a rock (such as permeability) can easily change with time and with the change in the composition of the fluids within the reservoir.

Or again it is entirely possible to have a highly feldspathic arkosic sand in which the feldspar has been weathered to such an extent that it has been largely gone over to kaolin with the possibility that some of its reactions to the passage of an electric current may be similar to those of a highly clayey rock such as a shale.

All of this again points to the necessity of learning more about the basic petrographic background of rocks before going too deeply into a purely empirical interpretation of geophysical parameters. Dr. Dickey's recent work on the electrical logging of the Franklin Oil Mine is a brilliant example of what should be done in this connection.

It is a pleasure to see that Messrs. Bays and Folk have kept their feet on the ground in their geophysical interpretation and have done a remarkably good piece of work in fitting geophysical and geologic information together in a most thorough and apparently very dependable way.

Their results certainly compare most favorably with anything that has been published on the geophysical logging of oil wells.

#### **Dr. W. V. Howard:**

The least satisfactory discussion of a paper is one which states that it is a complete analysis of the subject and is a thoroughly admirable presentation in every way. Such a discussion often indicates that the reviewer has a personal interest either in the authors or in their work or has not read the paper. None of these conditions is correct in this instance, but no other appraisal of the paper is possible.

The authors show how all of the different methods of geophysical logging operate instead of plugging one method alone. They give practical examples of the uses to which they can be applied in old wells, as

#### **REFERENCES**

- <sup>1</sup> Dickey, Parke A., "Natural Potentials in Sedimentary Rocks," A.I.M.E. Tech. Pub. No. 1625 (1943).
- <sup>2</sup> Krynine, Paul D., "Petrology and Genesis of the Third Bradford Sand." Penna. State College Min. Ind. Exp. Sta. Bull. 29, 134 p., 1940; see especially Ch. IV on "Texture and Pore Pattern" (p. 64-77).

well as in new ones. On reading the paper, the reviewer's only regret is that although all of the methods used were developed in connection with the oil industry, he has seen no discussion of the subject in the literature of oil which handles it as well as do the authors of this paper.

Congratulations are, as I have indicated, no discussion, but that is about all that is possible in this case.

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### COMMENTS FROM THE FLOOR

MR. C. D. ADAMS, Water Plants Superintendent,  
Public Service Co. of Indiana, New Albany,  
Ind.

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#### Mr. C. D. Adams:

We have one of Dr. Bays' co-workers in Indiana, Dr. Hagan. After drilling several test wells without finding an additional supply, we called upon Dr. Hagan to make a survey. The limestone in this particular area is rather shallow, averaging 40 to 45 feet, and the intent of Dr. Hagan's survey was to find a depression in the limestone area. He obtained very good results. In one well he estimated limestone at 70 feet and in the second at 80 feet. In the one it was found at 67½ feet and in the other at 76 feet.

After having watched the waterwitches, as they are called, going around with their hazel limbs, and after watching Dr. Hagan carry on his survey there is only one conclusion we can make: The geophysics survey water has taken the "itch" out of waterwitching.

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### CLOSURE

DR. CARL A. BAYS, Geologist and Engineer,  
Illinois State Geological Survey Division,  
Urbana, Ill.

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#### Dr. Carl A. Bays:

Mr. Folk and I both are deeply grateful for the kind and constructive comments on our manuscript made by the various discussers. As geologists, our policy has been to eye with suspicion all indirect methods of investigation such as those we have treated. From an engineering point of view, our

main objective has been only to keep our investigations in the field of practical utility. By use of geophysical measurements in conjunction with detailed geological information, as has been pointed out in the various discussions and by us, we reach interpretations as to geological and engineering conditions within a well or area. It is necessary to repeat that in both subsurface and surface surveys, as much knowledge of the geology as possible is fundamental.

Turning to some of the specific points raised in discussion:

The question of economics, whether the result justifies the cost, has been raised several times in connection with well surveys. We feel that geophysical logging has proved its worth in deep wells in Illinois, and we consider that geophysical logging is a *must* for any deep well on which a work-over job is planned. Many of our well owners and drillers feel that the expenditure of a few hundred dollars on logging wells that cost from a few to many thousands of dollars, is more than justified. We can show on any one of a number of the wells surveyed a saving greater than the entire expenditure on geophysical logging. With the conclusion of our own experimental investigations, it has been gratifying to see municipalities and industries decide to run complete geophysical logs at their expense to solve their own local problems. An advisory service by the experienced men on our Survey staff is maintained to interpret such surveys and to coordinate information. The complete geophysical log is standard practice in such cases.

Mr. Rose's remarks concerning the potential curve merit comment. As has been pointed out, in the Gulf Coast Region (and for that matter in many areas where potential curves are recorded, whether in oil or water wells), little relation is observed between potential values and permeability. However, in any area where electrofiltration, solely or dominantly, is the source of the potentials recorded, these values are related to permeability. With the exception of some disturbance by geochemical phenomena or stray currents, electrofiltration seems to be the major source of potentials in Illinois oil wells, so much so that in field practice arbitrarily assigned potential values are assumed to indicate certain permeabilities. We know from chemical studies of the brines that the potentials in oil wells are not primarily related to solution-concentration differences such as those described by Mr. Rose. In some cases good correlations between potential curves and permeability analyses of cores are worked out. In water wells

where we do not obtain a potential curve related to permeability, we try to change the natural conditions by (1) adding salt to create a solution-concentration-difference or (2) filling the hole to create electro-filtration potentials which are definitely related to permeability. We feel confident from close correlation of permeability as obtained from well yields and other data that in most cases the "high" negative potentials in the filled hole indicate permeability and that their relative values indicate relative permeabilities.

It should be pointed out in view of Mr. Ritzmann's remarks concerning core analyses, that we have run porosity and permeability analyses on at least some samples from all the formations in the section, using the standard Bureau of Mines technique. The Survey's cable-tool core-barrel has been made available for use in water wells, and analyses have been run on the principal formations from cores, outcrop samples, or the large shot-fragments bailed from wells after shooting. As a background to furnish the geological data for the interpretations made of geophysical logs, we have used (1) detailed microscopic examination of thousands of well cuttings; (2) intensive outcrop studies, both in the area of study, primarily in northern Illinois in this case, and the closest area of outcrop of the principal aquifers, Wisconsin and north-central Illinois; (3) study of insoluble residues of the carbonate rocks, made by digesting them in hydrochloric acid; (4) extensive size-analyses of the clastic rocks; (5) studies of heavy accessory materials in the sandstones; (6)

chemical stains to differentiate limestone from dolomite; (7) the core-analyses; and (8) a number of additional methods such as sphericity studies, thin-section studies, micro-fauna identifications, et cetera. The inclusion of these geological studies as part of the present paper did not seem advisable as they constitute a part of a report on the ground-water geology of northeastern Illinois now being prepared, but in the consideration of geophysical data it should be kept in mind that these geological studies have been closely integrated and that many of our interpretations would not be justified in our own minds without these additional corroborating data.

The treatment of earth-resistivity surveys was purposely brief and intended primarily as another documentation of the success of this method. All of Mr. Ritzmann's remarks concerning this method are well taken. Several different graphical methods of the solution of multilayer resistivity problems have been used by the men doing this work for the Survey in the past eleven years. In many cases some compromise has necessarily been made between correct handling of these data and utility for water-works superintendents and engineers.

We have appreciated the opportunity to describe to this Society the progress made so far in our work on the applications of geophysical methods to ground-water problems. The comments on our work and the prospect that others can obtain some benefit from it in giving wider application to these methods has made the presentation of this discussion a pleasure.









